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DECAY OF PARTICLE CONCENTRATION AS A FUNCTION OF ROTATION RATE IN A ROTATING DRUM CHAMBER

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14. ABSTRACT

Rotating drum chambers are used to keep aerosol particles suspended for an extended period of time to study aging effects. The drums are designed to rotate on a horizontal axis, using centrifugal force to counteract the effects of gravity on small particles. Theoretically, there are different rotation rates for different particle sizes that optimize suspension time. Several different methods have been used to calculate the optimal rotation rates with varying results. This report will compare these mathematical models to experimental results.

15. SUBJECT TERMS

Aerosol	Rotating drum	Particle distribution

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PREFACE

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DECAY OF PARTICLE CONCENTRATION AS A FUNCTION OF ROTATION RATE IN A ROTATING DRUM CHAMBER

1.   INTRODUCTION

The capability to age aerosols is useful to a wide range of research. Many studies including inhalation toxicology and environmental fate could benefit from extending the suspension time of particles. Rotating drum chambers are sometimes used to accomplish this task because at the proper rotation rate, particles in a rotating drum chamber can remain suspended for days and, theoretically, months at a time.

Several mathematical models have evolved to calculate the optimal rotation rate for different size particles with varying results. For example, Asgharian and Moss (1992) conclude that for rotation rates calculated between 0.1 and 10 rpm, the optimal rotation rate is independent of particle size for particles smaller than 5 μm.[*] However, Gruel, Reid and Allemann (1987) claim that, "For particle diameters of 10 μm or less, the optimal rotation rate is essentially independent of particle size."[**] It is speculated that as particle size increases, so does the sensitivity to rotation. In these models, only the gravitational and viscous drag forces are considered. Forces due to electrostatic, diffusion, pressure gradient, and mutual collision are ignored. Also ignored is the aerosol's activity along the horizontal axis. Only particle movement around the axis of rotation is taken into account. Experimentally, there is very little information on the rotating drum chamber. The purpose of this research is to characterize a rotating drum chamber and compare experimental data to the mathematical models.

2.   EQUIPMENT

The rotating drum chamber that is used in these experiments is made of stainless steel and has a maximum storage volume of 750 L. The outside is 1.39 m in length and 1 m in diameter. The inner wall of the drum has an airtight-mirrored finish. There is a piston inside the drum to draw air into or out of the drum as necessary. On the outer face opposite the piston, there are four ports for taking measurements: one along the horizontal axis (axis of rotation), then at 0.26, 0.36, and 0.45 m away from the axis. The rotational rate ranges from 0.01 to 10 rpm. The computer that controls the drum has a touch screen that allows for ease in changing rotation rate and piston movement (Figures 1 and 2).

The equipment that is used to sample the air inside the drum is an Aerodynamic Particle Sizer, or APS. It can characterize size distributions for aerosols consisting of particles with aerodynamic diameters from 0.5 to 20 μm. The aerodynamic diameter is the most important size parameter because it determines a particle's airborne behavior (Figure 3).

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[*] Asgharian, B.; Moss, O.R. Particle Suspension in a Rotation Drum Chamber when the Influence of Growth and Rotation are Both Significant. *Aerosol Sci. Technol.*, **1992**, 17; pp 263-277.

[**] Gruel, R.L.; Reid, C.R.; Allemann, R.T. The Optimum Rate of Drum Rotation for Aerosol Aging. *J. Aerosol Sci.*, **1987**.
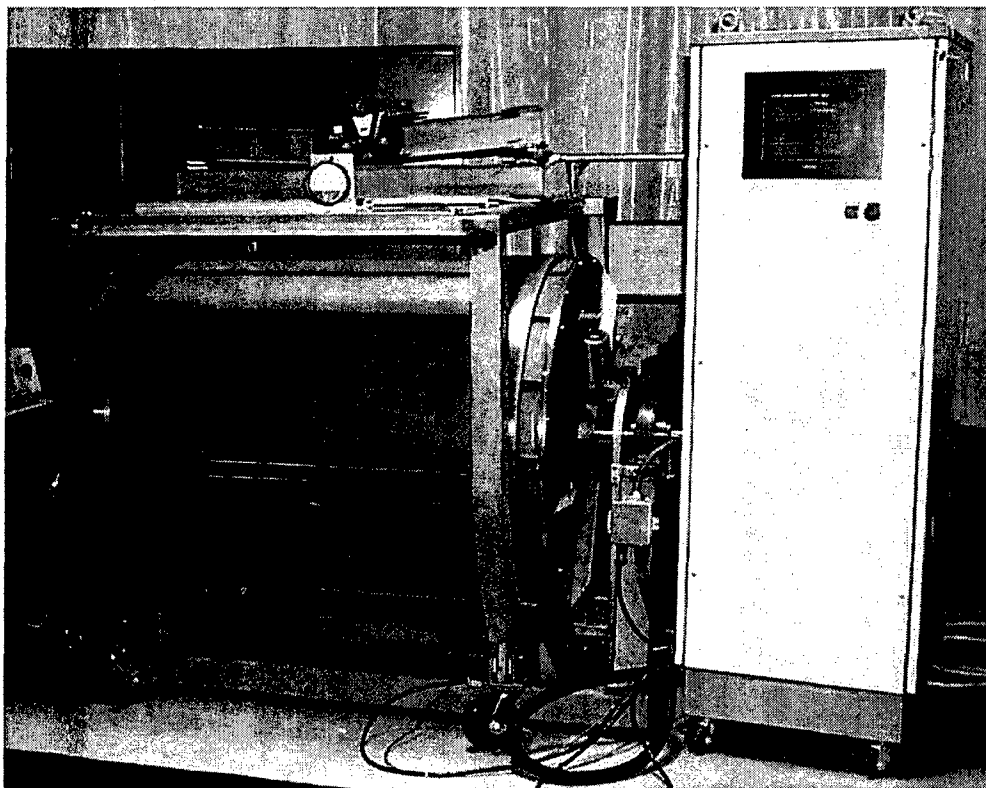
Figure 1. Rotating Drum Chamber and Computer
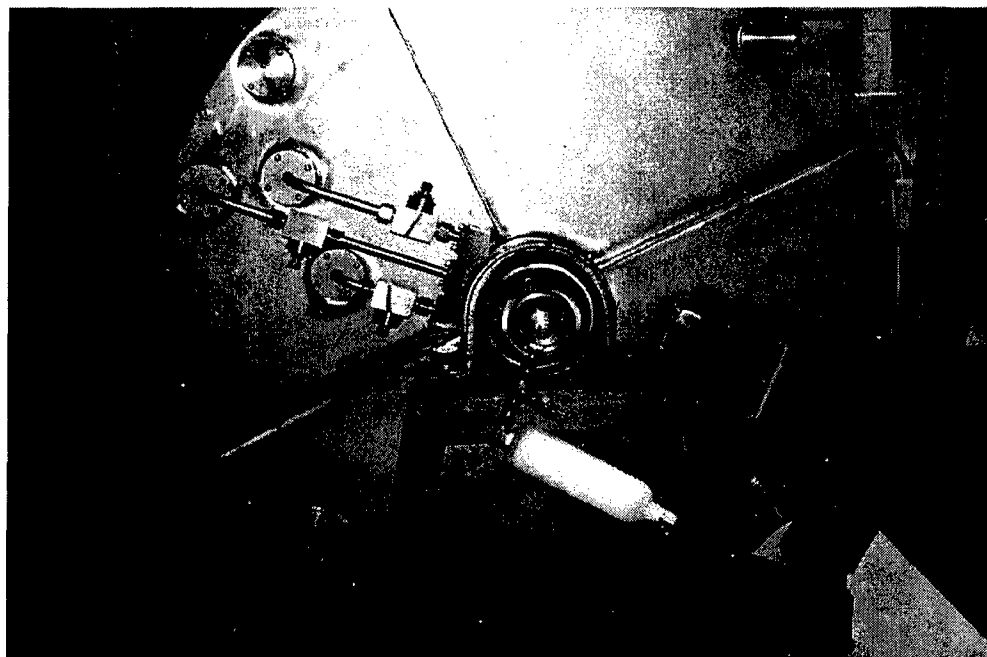
Figure 2. Ports from Which Measurements are Taken
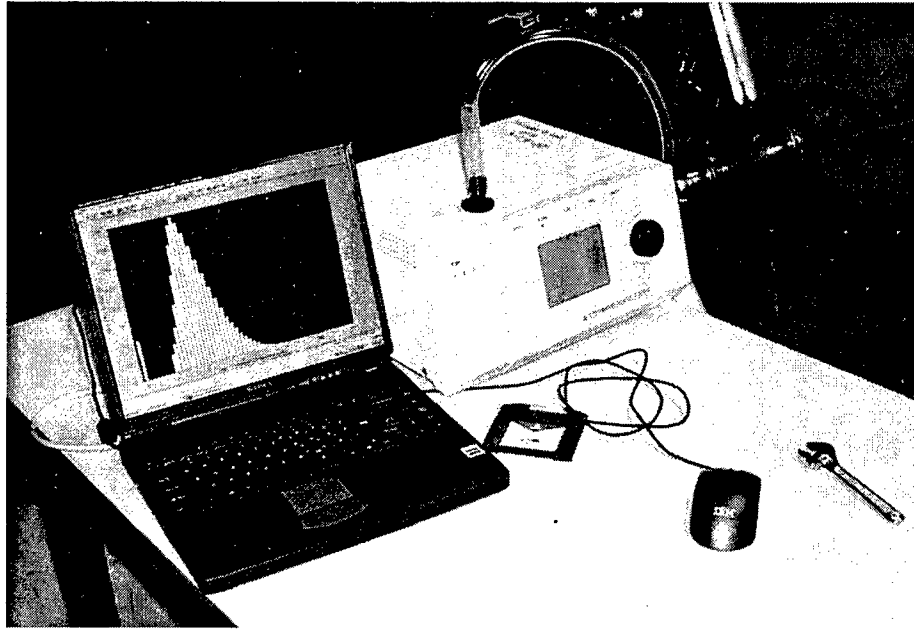
Figure 3. Aerodynamic Particle Sizer with Computer Control

A combination of 3 and 6 µm aluminum oxide powder is aerosolized for use in the characterization. A sonic nozzle (Figure 4), is used to disseminate the aluminum oxide. The nozzle is designed to break up and disseminate fine powders into their smallest component sizes. It works using air pressure to create enough shear force at the nozzle tip to overcome Vanderwaal and adhesive forces. The particle size distribution is shown in Figure 5. The lack of bi-modal distribution is most likely due to the electrostatic deposition of the larger particles during dissemination.

Figure 4. Sonic Nozzle

Figure 5. Particle Size Distribution of a Combination of 3 and 6 μm Aluminum Oxide
After Dissemination

3.   PROCEDURES

The rotating drum chamber is set in motion to the desired rotational speed. The
piston is then used to purge all of the air out of the drum. Using the sonic nozzle, the aluminum
oxide powder is disseminated into a large, durable trash bag. One end of a Tygon tube is then
placed inside the open end of the trash bag. The trash bag is kept as airtight as possible by
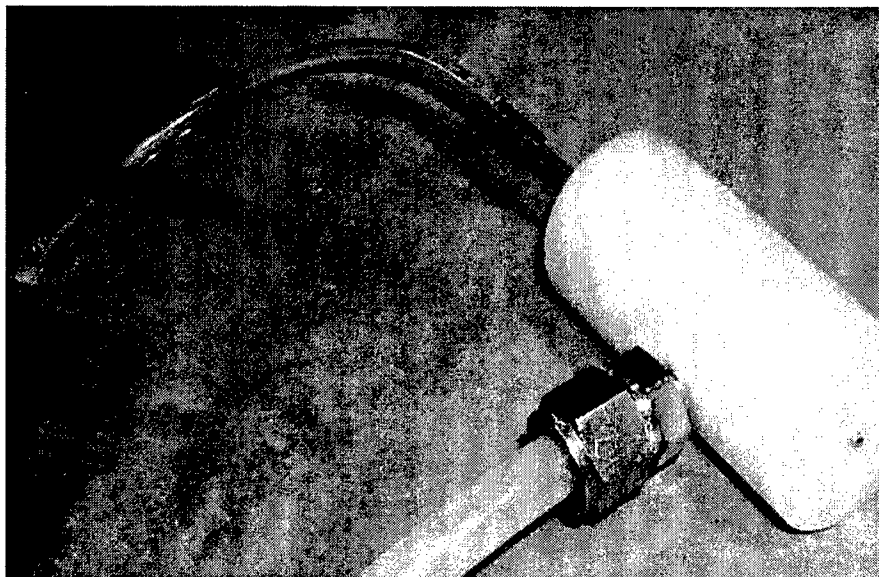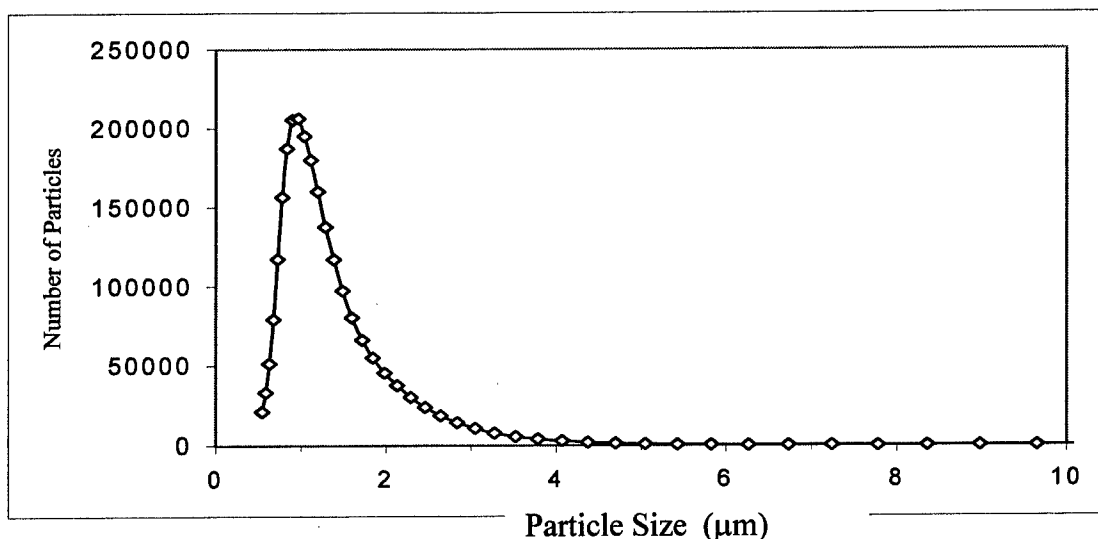grasping the bag around the tubing. The other end of the Tygon tube is then attached to the open
port of the rotating drum chamber. The piston is then used to draw the aerosol from the bag and
into the chamber.

An APS is used to measure the decay of aerosol concentration in the rotating
drum chamber at various rotation rates. This is accomplished by taking an APS reading
immediately after the aerosol is disseminated, then additional readings are taken approximately
every 4 hr, as time allows, for 96 hr. The particle counts for each time interval are summed and
then divided by the sum of particles in the initial reading. This calculation yields a percent of the
initial particles that have remained suspended at the different time intervals. The same method is
used to determine the decay of aerosol in the drum when it is stationary. The data collected from
the stationary drum is used as a reference for the data collected at the different rotation rates. At
the completion of each test, the piston is used to purge the drum of any remaining aerosol. It
should be noted that some of the tests were cut short due to uncontrollable circumstances.

3.1   Test 1.

At a rotation rate of 1 rpm, disseminate 1 g of 3 μm aluminum oxide and 1 g of 6 μm aluminum oxide. Take the initial reading after 15 min at each port. Take additional readings at each port every 4 hr (as time allows). Continue to do this until the initial concentration of total particles is depleted by 70 %.

Note: After 24 hr almost all particles above 3 μm have deposited. For the next series of tests, readings are taken every hour of the first day to get a more detailed timeline of when the larger particles are depositing. Also, the results of the first test are unusual in the sense that the readings claim that there are more small particles in the 4-24 hr then there are at the first reading. The APS is indicating a high concentration of particles during those hours, so the amount of aluminum oxide disseminated is reduced to 0.5 g of each size for the next series of tests.

3.2   Tests 2-7.

At a rotation rate of 0, 0.5, 2, 4, 6, and 8 rpm, disseminate 0.5 g of 3 μm aluminum oxide and 0.5 g of 6 μm aluminum oxide. Take the initial reading after 15 min at each port. Take additional readings at each port every 4 hr (as time allows). Continue to do this for 96 hr.

Note: The APS indicated high concentration again, so for 4 and 6 rpm tests, 0.25 g were used. There were no discernable differences in the data since all of the readings are calculated as a percentage of the initial concentration. The presence of high concentration in the first few hours may cause a slight margin of error, but nothing significant enough to measure. Additionally, there does not seem to be any difference in the readings at the different ports (Figure 6), so for future tests, readings will only be taken from ports 1 and 4.

3.3   Test 8.

Based on the data analysis of the previous tests, 2 and 4 rpm have the lowest drop off rate of total initial particles. Repeat the previous test at a rotation rate of 3 rpm to see if it is optimal.

Note: For reasons unknown, the 3 rpm test results did not fall where expected (Figure 7).

3.4   Test 9.

At a rotation rate of 2 rpm, repeat tests in the same manner as before using 2 g of 6 μm aluminum oxide.

Note: There are fewer particles per gram of the 6 μm aluminum oxide because the particles are more massive. Therefore, our counts are much lower than before. For this reason, 4 g will be used in the following tests.
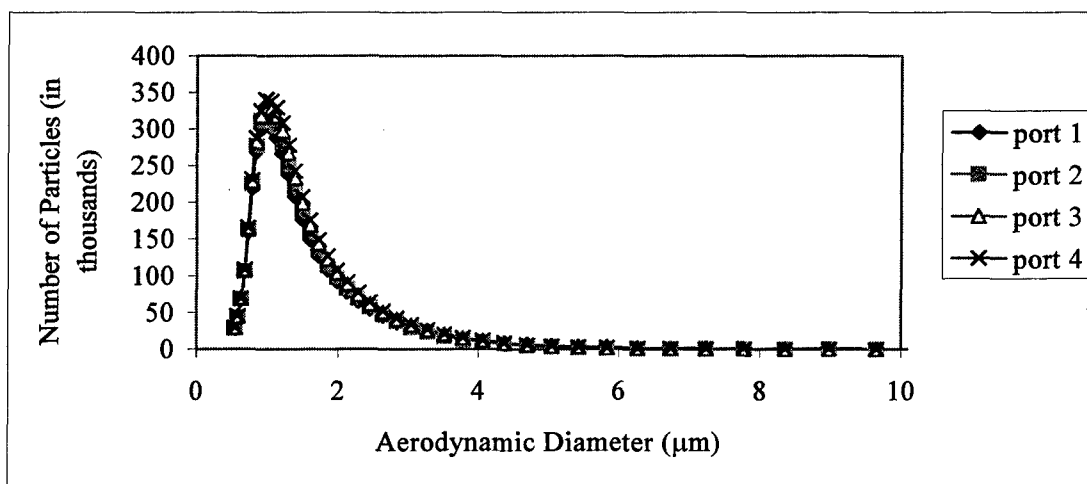
Figure 6. Distribution of Suspended 3 and 6 µm Aluminum Oxide Particles
Throughout the Drum
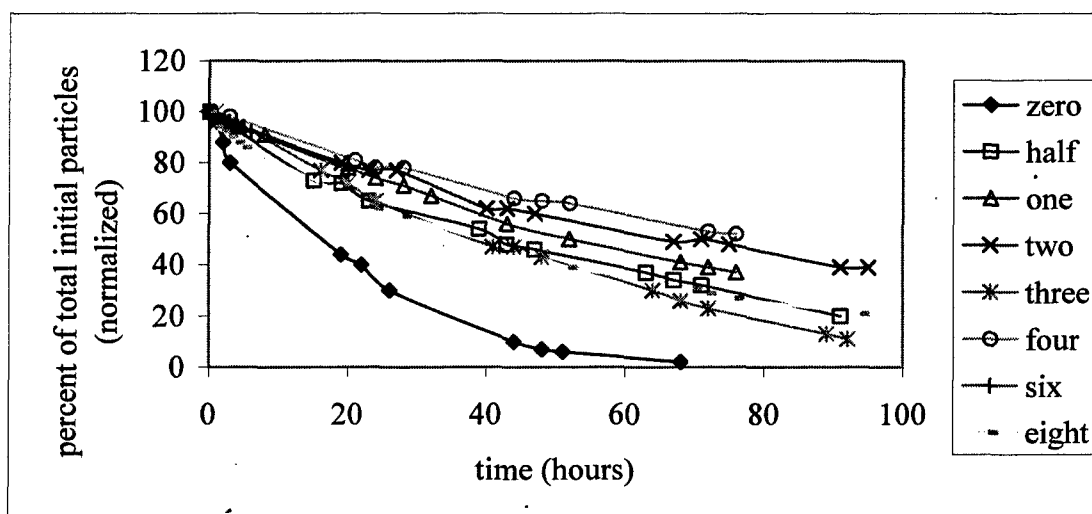

Figure 7. Suspension Decline of 3 and 6 µm Aluminum Oxide Particles Over Time
at Different Revolutions Per Minute

3.5   Tests 10-13.

At a rotation rate of 0, 4, 6, and 8 rpm, repeat tests in the same manner as before
using 4 g of 6 µm aluminum oxide.

4.   RESULTS

During some of the tests, the concentration of 1 and 2 µm particles increased within the first 4 to 6 hr, and then began to decrease. The speculation for this occurrence is that it takes a few hours for the air inside the drum to homogenize. This measured event disagrees with the theory. In the mathematical models, it is assumed that there is only particle movement around the horizontal axis. Figure 8 shows what the trajectory of a particle should look like inside the drum based on the mathematical model.[*] Movement along the horizontal axis is not taken into consideration. This trend is likely due to the addition of the piston in this drum. There is no piston in the theoretical drum. The movement of the piston while drawing air into or out of the drum sets the particles in motion along the axis. The larger particles (above 2 µm) deposit too quickly to exhibit this phenomenon.

The aerosol distribution of the Goldberg Drum is uniform. Figure 6 is a generic depiction of the aerosol uniformity during these tests. This particular reading was taken immediately after dissemination of test 2. It clearly shows that the difference in concentration from port to port is negligible. This is an indication that the particle suspension is uniform throughout the Drum. This figure also shows that most of the particles larger than 2 µm have not survived dissemination for tests 1-8. Based on this graph, we will consider the combination 3 and 6 µm aluminum oxide to have a particle size of approximately 1 µm.
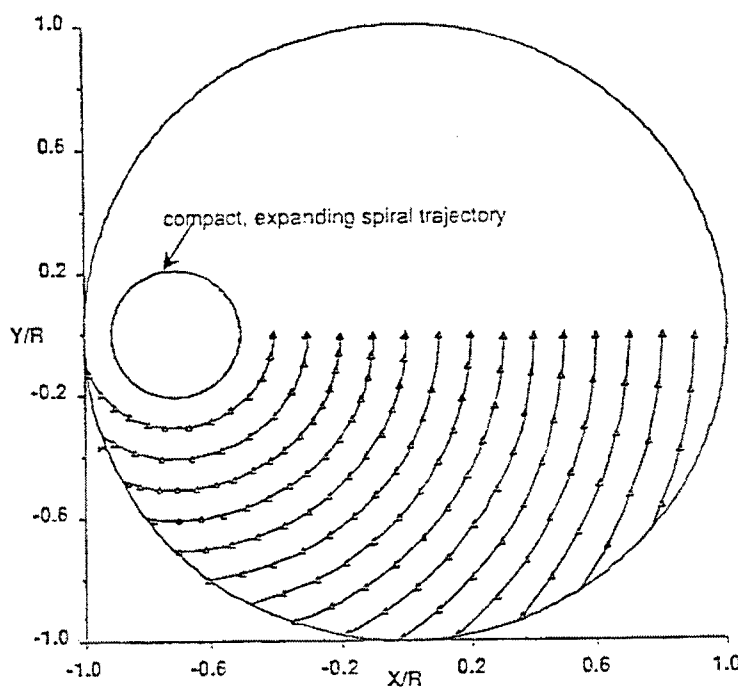

Figure 8. Theoretical Trajectory of a 20 µm Particle at 1 Revolution Per Minute*

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* Aerosol Science and Technology: Particle Suspension in a Rotating Drum Chamber When the Influence of Gravity and Rotation are Both Significant, **1992**, 17; pp 263-277.

Having taken the particle size to be predominantly 1 µm, the particle counts are totaled and graphed as a function of the percent of initially suspended particles with respect to time for all the measured rotation rates. Figure 7 represents the data from tests 1-8.

Figure 7 indicates that the two and four rpm tests achieved the best results. It was speculated that the results of the 3-rpm test should fall in line with the results of 2 and 4 rpm tests. It is unknown why this did not happen. Figure 7 concludes that the drum is effective for 1-µm particles. Based on this data, the drum kept nearly 50 % of the one 1 µm particles suspended after 96 hr at a rotation rate of 2 rpm. In the stationary drum (zero rpm), more than 50 % of the initially suspended particles had deposited within the first 20 hr.

The data, however, does not agree with the mathematical models. One of the models claims that nearly all of the initially suspended 1µm particles should remain suspended after 14 days. Figure 9 depicts the theoretical decay of the initially suspended particles with respect to time for each particle size's optimal rotation rate.[*] The reasons for the drastic differences between the data and the theory will be considered in the conclusions of this paper.

For tests 9-13, there was a slightly larger range of particle sizes than in tests 1-8. The size distribution of the 6 µm aluminum oxide after dissemination is shown in Figure 10. The data for tests 9-13 cannot assume a 1 µm particle size because of the size distribution. Therefore, the data will be broken into 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 µm sizes.
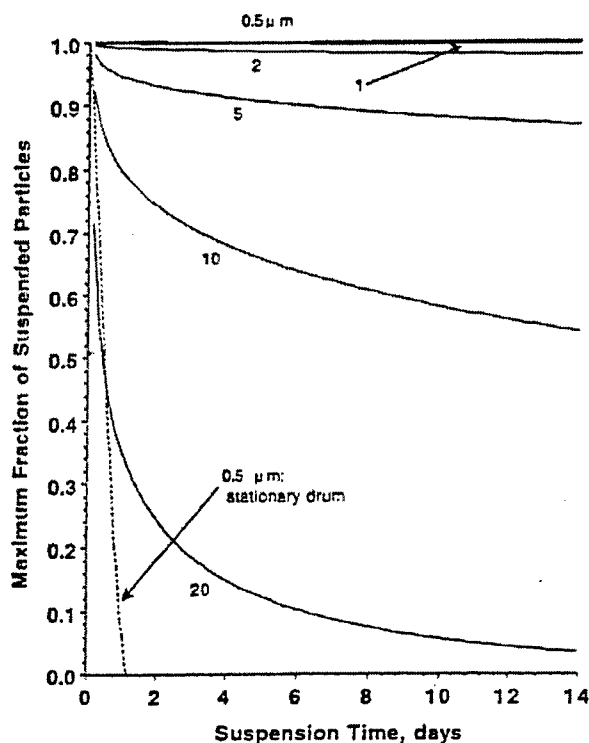

Figure 9. Theoretical Decay of Initially Suspended Particles at Each Particle Size's Optimal Rotation Rate

[*] Aerosol Science and Technology: Particle Suspension in a Rotating Drum Chamber When the Influence of Gravity and Rotation are Both Significant, 1992, 17; pp 263-277.
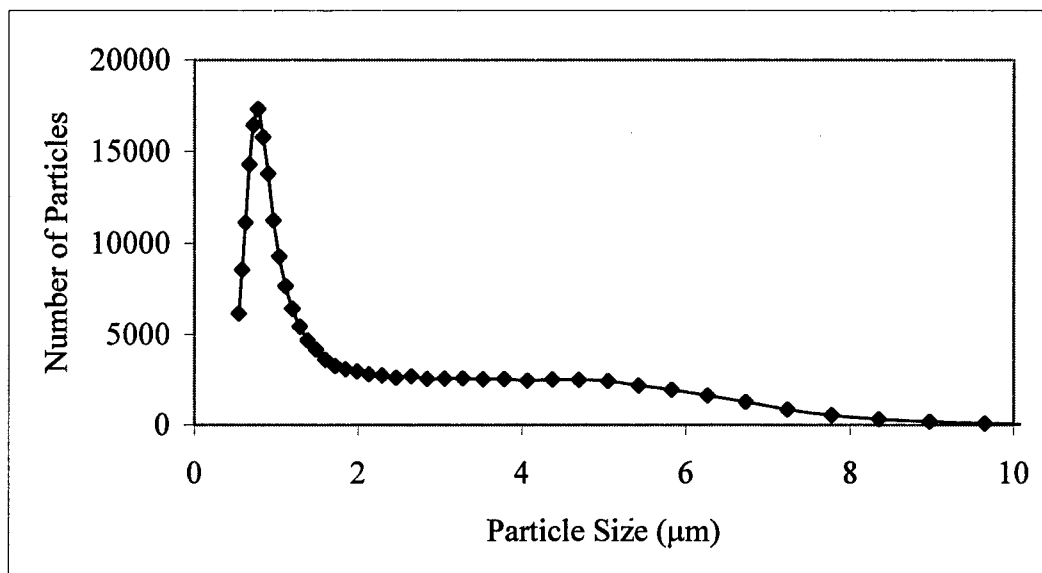
Figure 10. Particle Size Distribution of 6 μm Aluminum Oxide Particles After Dissemination

Figures 11-20 show the results of tests 9-13. Each particle size is graphed as a function of the percent of initially suspended particles with respect to time for all the measured rotation rates. The scales of the graphs vary. This is because the larger particles deposit much faster. Most of the tests ran for 24 - 48 hr. However, since the larger particles completely deposited within the first few hours, the scale of the graph was changed to show more detail. For this same reason, some of the rotation rates were excluded from the graphs due to overlapping.
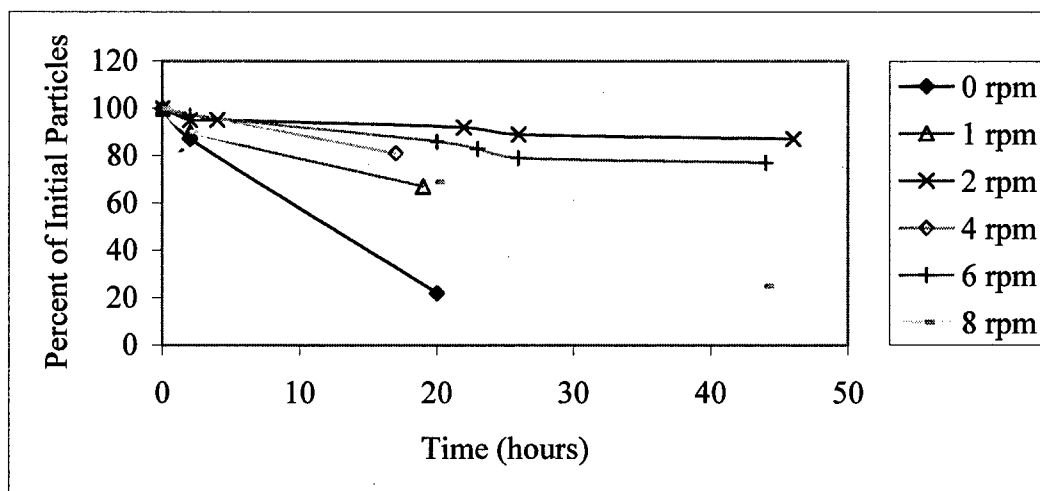

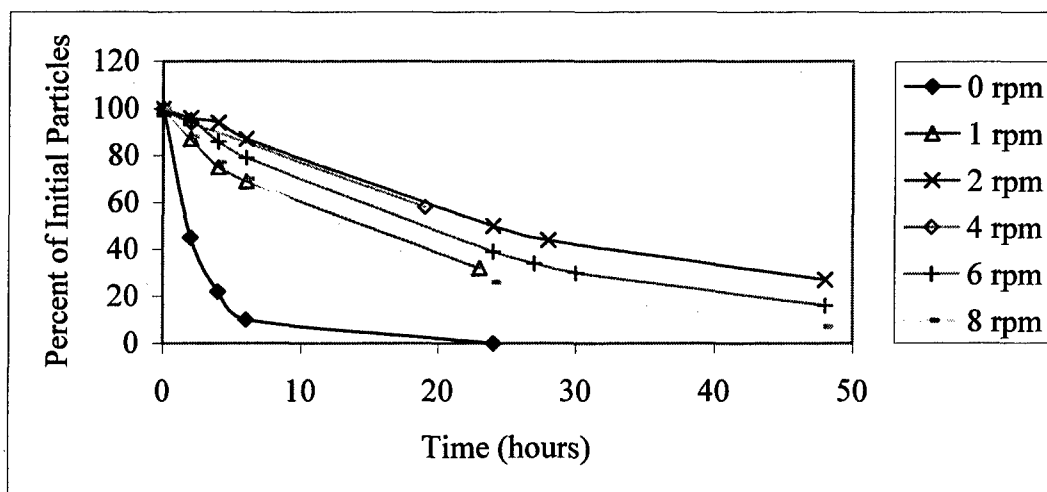Figure 11. Decay of 1 μm Particles Over 48 hr at Different Rotation Rates

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Figure 12. Decay of 2 μm Particles Over 48 hr at Different Rotation Rates
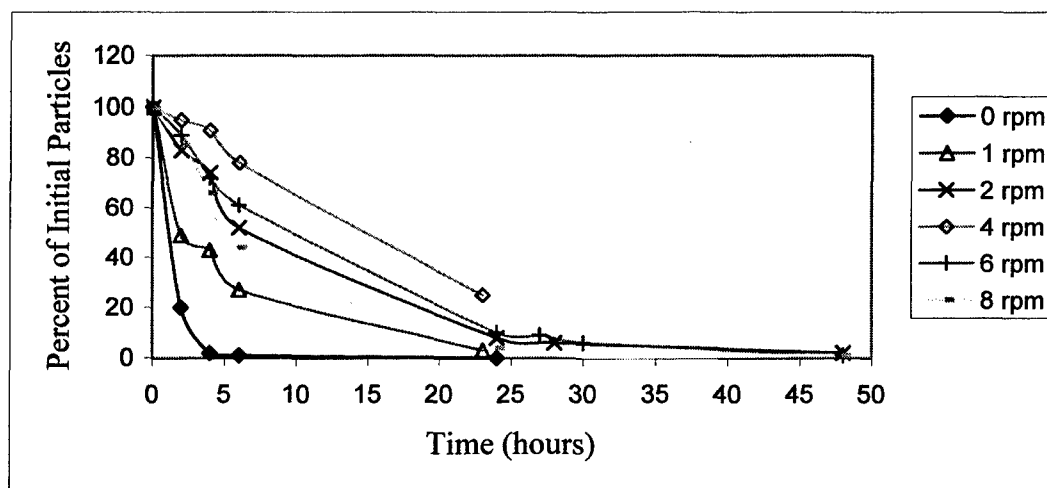

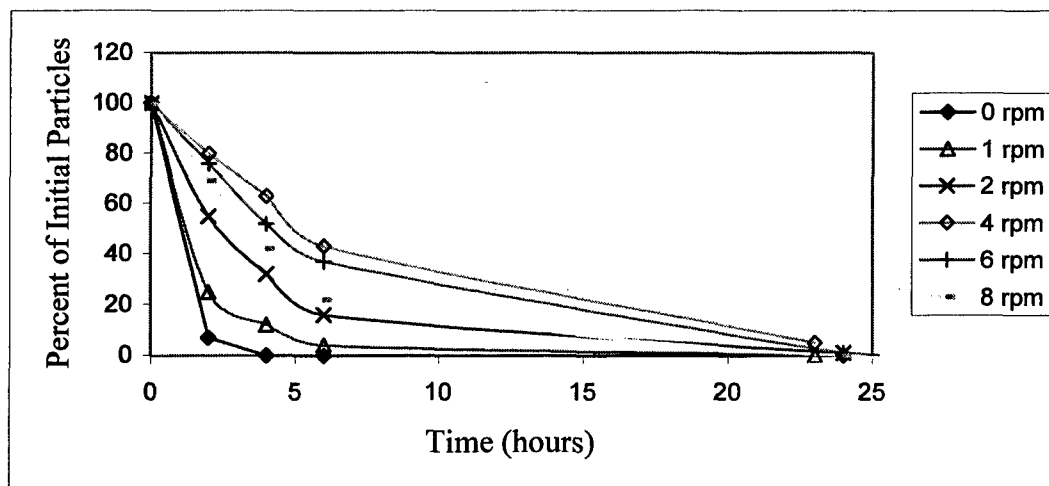Figure 13. Decay of 3 μm Particles Over 48 hr at Different Rotation Rates

Figure 14. Decay of 4 μm Particles Over 24 hr at Different Rotation Rates

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Figure 15. Decay of 5 μm Particles Over 24 hr at Different Rotation Rates

Figure 16. Decay of 6 μm Particles Over 6 hr at Different Rotation Rates

Figure 17. Decay of 7 μm Particles Over 6 hr at Different Rotation Rates

17

Figure 18. Decay of 8 μm Particles Over 4 hr at Different Rotation Rates

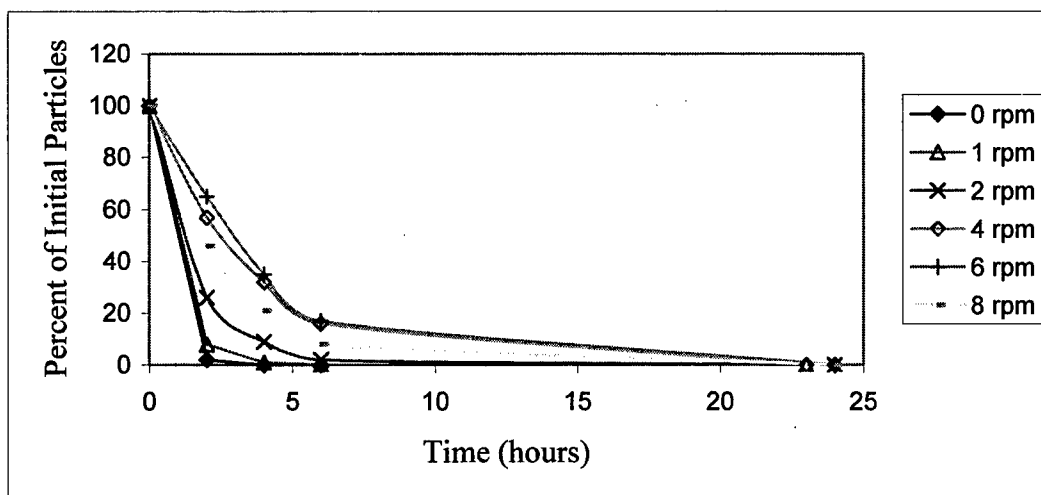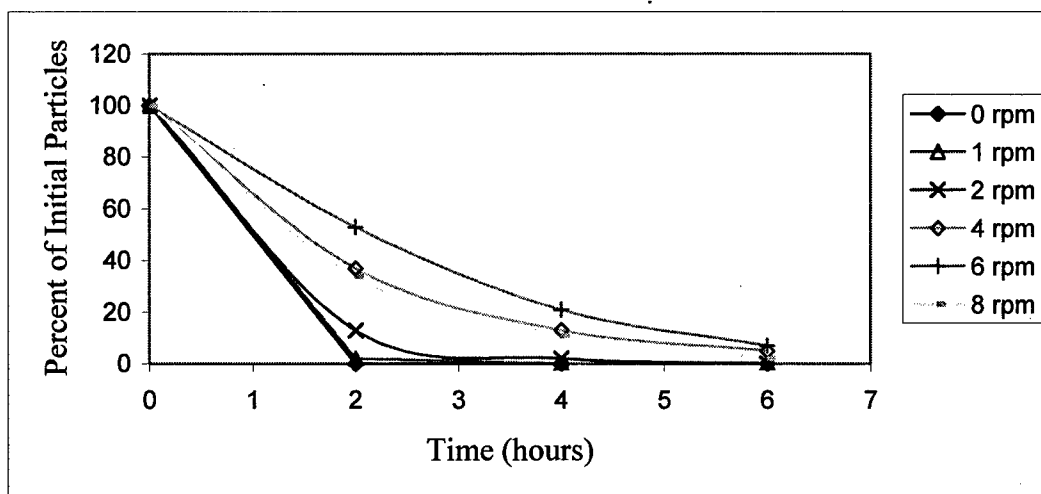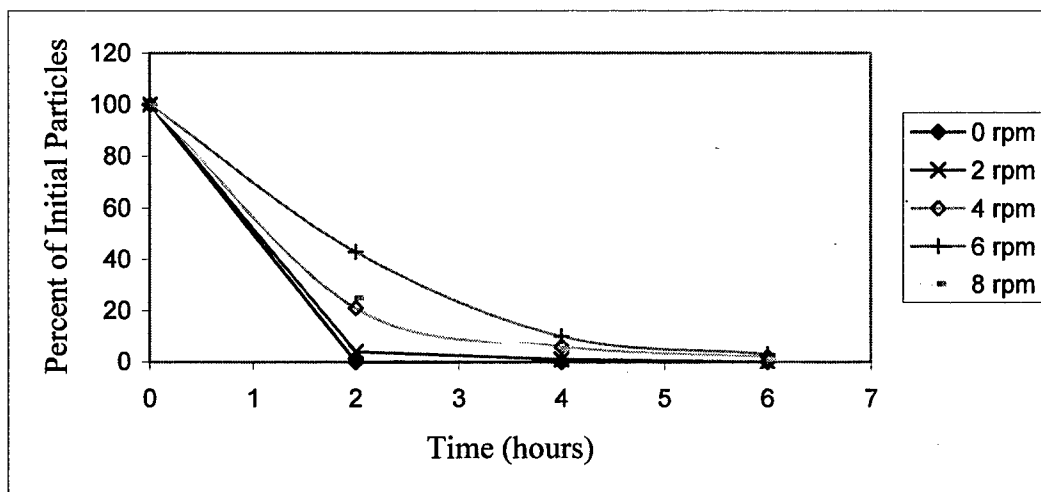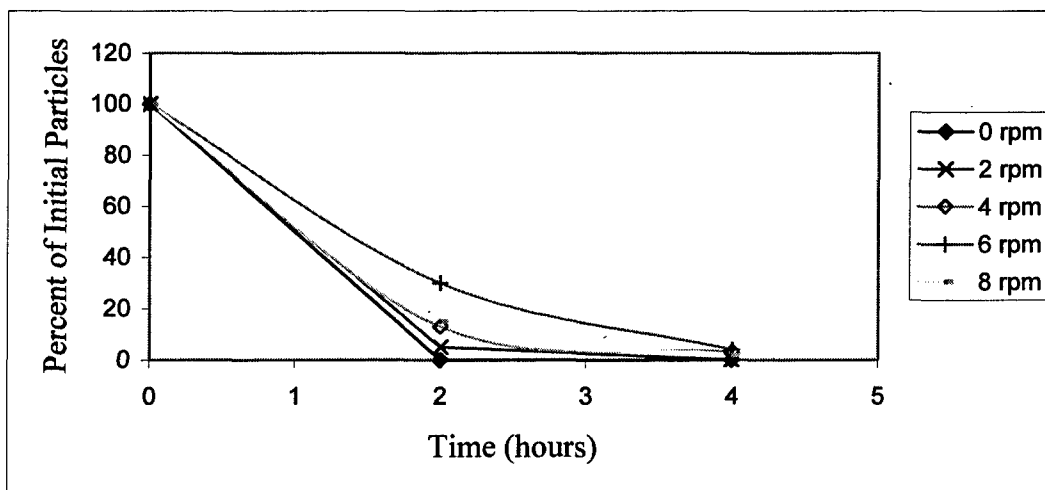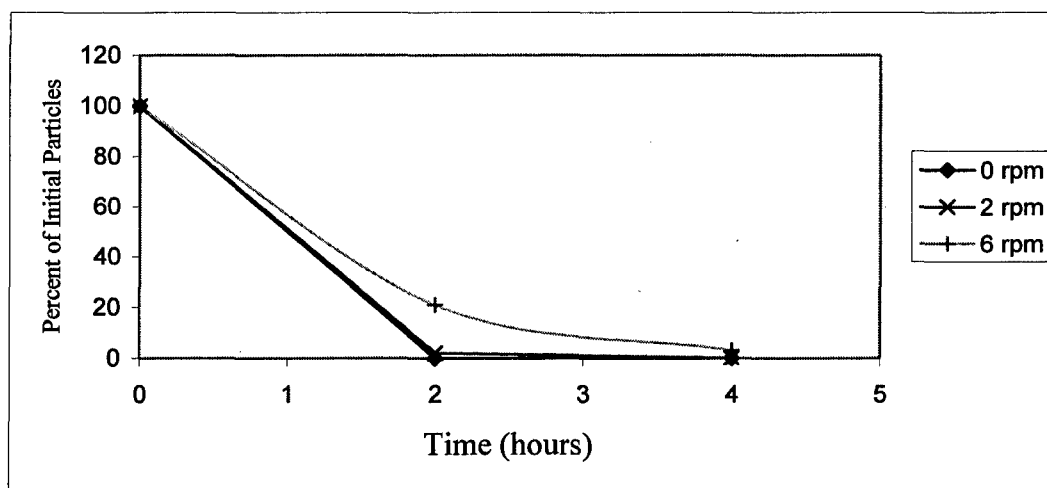Figure 19. Decay of 9 μm Particles Over 4 hr at Different Rotation Rates
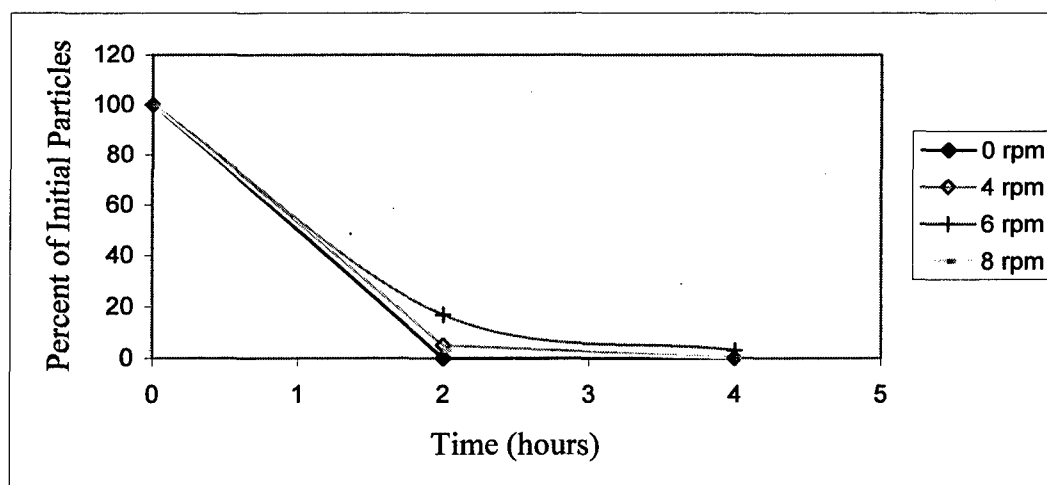

Figure 20. Decay of 10 μm Particles Over 4 hr at Different Rotation Rates

These graphs qualitatively agree with the theory. The mathematical model shows that as the particle size increases, so does the optimal rotation rate.[*] Quantitatively, however, the test results differ from these models. The theory shows optimal rotation rates between 0.3 and 1.5 rpm, whereas the test results show optimal rotation rates between 2 and 6 rpm.

It is shown in Figures 11 and 12 that 2 rpm is the optimal rotation rate for 1 and 2-μm particles. Slightly less efficient are 4 and 6 rpm. The least effective rotation rates for 1 and 2 μm are 1 and 8 rpm. All of the rotation rates, however, show a significant extension of particle suspension time over the zero rpm. These results also closely agree with the results of tests 1-8. This indicates that the tests are reproducible and consistent.

In Figures 13 and 14, 4 rpm is shown to be the most effective rotation rate for 3- and 4-μm particles. Following the 4 rpm are the 6 rpm, 2 rpm, 8 rpm and 1 rpm decreasing slightly, respectively. A trend is already emerging showing that the optimal rotation rates do, in fact, increase as particle size increases.

For the 5, 6, 7, 8, 9, and 10 μm particles, 6 rpm is shown to be the optimal rotation rate. Figures 15 through 20 indicate that, for most of these particle sizes, 4 rpm and 8 rpm are more effective than the 1 rpm and 2 rpm. None of the rotation rates, however, managed to keep any of these larger particles suspended past 6 hr.

5. CONCLUSIONS

For every particle size and rotation rate measured, the rotating drums chamber yielded better results than a stationary drum. However, more work needs to be done to increase the effectiveness of suspending large particles for extended periods of time. There is also a large discrepancy between Asgharian and Moss's mathematical model and the experimental data. This may be due to the fact that the theory ignores forces due to electrostatic, diffusion, pressure gradient, and mutual collision. The mathematical model of the drum also excludes any movement of particles along the axis of rotation; only movement around the axis is considered.

Even while these discrepancies are being worked out, the rotating drum chamber can be a valuable tool. The data so far shows a notable increase in suspension time for 1 μm particles. This attribute has many applications in aerosol research. For example, Bg, a low level biosimulant for anthrax, is approximately 1 μm. A rotating drum chamber could be used to keep Bg suspended for days to study its airborne behavior under different environmental conditions. These tests may eventually improve testing and characterization of biodetection systems. Asgharian and Moss propose the usefulness of the rotating drum chamber in inhalation toxicology studies. "Maintaining a high number concentration of generated particles is desirable in long-term animal exposure studies where the generated particles are scarce, expensive, or highly toxic. Rotating drum chambers have potential use in providing a stable atmosphere of well-characterized respirable particles for periods lasting from hours to days for use in inhalation toxicology studies."[*]

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[*] Asgharian, B.; Moss, O.R. Particle Suspension in a Rotation Drum Chamber when the Influence of Growth and Rotation are Both Significant. *Aerosol Science and Technology,* **1992**, 17; pp 263-277.